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EFFECT OF WORLD-WIDE CHANGES OF ISOTROPIC COSMIC RAY INTENSITY ON THE DAILY VARIATION OF COSMIC RAYS

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ABSTRACT. Various methods of evaluating the 12 bi-hourly values required for a study of the daily variation of cosmic ray intensity are discussed. Estimates are obtained of the distortions produced in the genuine daily variation due to slope, curvature and short-term effects of the world-wide fluctuations in isotropic cosmic ray intensity. A method for correcting for such effects is suggested and examined critically.

I. INTRODUCTION

The daily variation of cosmic ray intensity is a very important tool for the study of anisotropy of cosmic rays. Daily variation is usually studied by examining the form of the daily curve as a whole or by resolving the same into its Fourier components. It can be studied for individual days, if the statistical accuracy of the data is good enough, or for averages over groups of days. For data having large statistical errors on individual days, histograms of harmonic components obtained for individual days could still lead to useful conclusions.

However, while studying the daily variation of cosmic ray intensity, allowances are to be made for the effects due to world-wide changes of the isotropic cosmic ray intensity as these are likely to distort the true form of a genuine local-time daily variation. Whereas the possibility of such distortions is recognised by workers in this field, some of the recently published results seem to indicate that the extent of these distortions is not fully appreciated. The purpose of the present communication is to estimate the magnitude of such distortions under various conditions and for various aspects of study of the daily variation.

II. METHODS OF STUDY OF DAILY VARIATION

The basic requirement for a study of the daily variation is the evaluation of hourly or bi-hourly percent deviations from mean. Since most of the workers use bi-hourly deviations, we will henceforth consider only these. Percent bi-hourly deviations are usually obtained by the following methods :—

Method A : Evaluating the arithmetic mean of 12 successive bi-hourly values and expressing each bi-hourly value as percent deviation from this mean.

Method B : Applying correction for the linear gradients of cosmic ray intensity by subtracting the 0 hour value of one day from the 0 hour value of the next day. The difference so obtained is expressed as percentage of the day's mean. If this percentage value is designated as d, one subtracts the factor $\left(\frac{n-6.5}{12}\right)\times d$ from the nth bi-hourly deviation obtained by method A above.

Method C : Applying correction for the linear gradients by evaluating moving averages of 12 successive bi-hourly values and subtracting these from the original bi-hourly values. Since a mean of 12 successive values has an hour of centering not coincident with any bi-hourly value but lying half-way between two bi-hourly values, two alternatives are usually adopted :

(i) Moving averages of 12 bi-hourly values are further subjected to moving averages over 2 consecutive values so that the new means so obtained have centering coincident with the original bi-hourly intervals.

(ii) Moving averages are calculated for 13 successive bi-hourly values instead of 12 sucessive values so that the centering is the same as for original bi-hourly values.

In principle, procedure (ii) is less rigorous; because moving averages over 13 consecutive bi-hourly values leave some residual daily variation in the means. In practice, both methods give almost similar results.

Fig. 1 is an illustration of the three methods and the daily variations obtained by using them for a sample bi-hourly data for the neutron monitor at Sulphur Mountain for September 21—25, 1957, when the cosmic ray intensity undergoes a depression of about 10% in 2 days and then recovers to almost its original values in the next 2 days. The dotted line at the top (Curve X) is the plot of original bi-hourly values while the full curve Y superimposed on it is the plot of moving averages over 12 consecutive bi-hourly values. Curves A, B, C show the daily variations obtained by methods A, B and C respectively.

The following characteristics will be noticed from Fig. 1 :

(a) The daily variation obtained by method A is not corrected for linear gradients of the cosmic ray intensity and hence bi-hourly percent deviations for the 1st day (September 22, 1957) are positive for the first half of the day and negative for the latter half, creating a false impression of an early morning maximum of the daily variation. For the second day, the daily variation is characterised by a minimum which is coincident with the point of inflection in the general trend of intensity change. On the third day, the pattern is reverse to that of first day, creating a false impression of afternoon maximum.

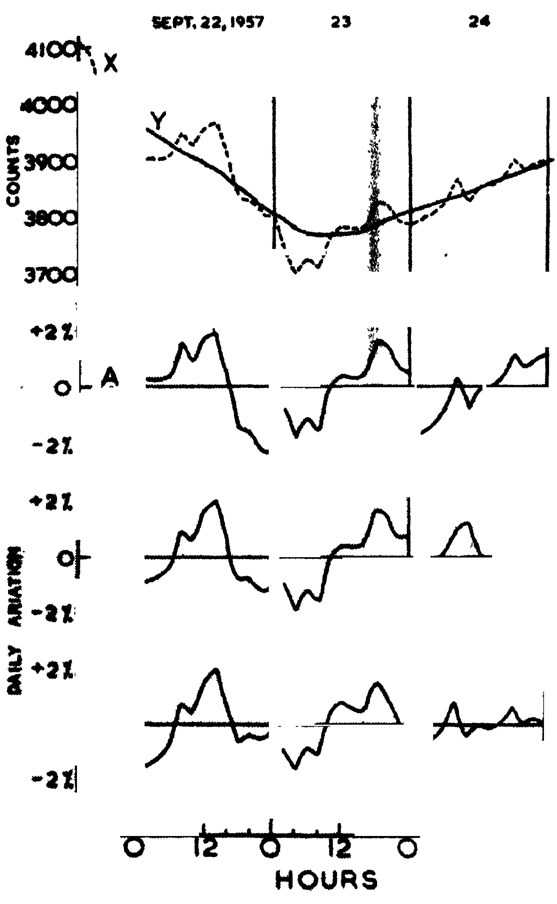

Fig. 1. Bi-hourly values and daily variation for neutron intensity at Sulphur Mountain for September 21–25, 1957.

(b) The daily variation obtained by method B is comparatively free from effects due to gradients on the 1st and 3rd day. However, for the 2nd day, the correction factor has been almost zero as the cosmic ray intensity has gone down and recovered again and the 0 hour values at the beginning of the second and third day are almost the same. Hence the daily variation on the second day is the same as the daily variation for second day obtained by method A.

(c) The daily variation obtained by method C is less affected by effects due to gradients as compared to the daily variations obtained by methods A and B.

III. COMPARISON OF METHODS *A* AND *C* FOR THE STUDY OF VARIOUS ASPECTS OF DAILY VARIATION

As seen in the previous section, the daily variation obtained by method A is subject to distortions due to gradients in cosmic ray intensity. If method B is employed, these effects are reduced to some extent but not fully, because the gradient is evaluated only from two bi-hourly values. In method C, the gradient is estimated at every bi-hourly interval by averaging 12 consecutive bi-hourly values around the bi-hourly interval under consideration. Method C is, therefore, superior to methods A and B. Since methods A and C are at the two extremes and method B has intermediate characteristics, we will consider only methods A and C and estimate the order of magnitude of distortions involved when linear gradients are neglected in various types of analysis.

(1) *Study of daily variation averaged over a group days*

The effect of the gradients is to introduce extra contributions in the bi-hourly percent deviations. Larger the gradients, larger will be the distortions. However, gradients are both positive and negative. Hence for averages over a group of days, it is expected that effects due to gradient of opposite signs will cancel each other to some extent. The cancellation will be more effective for larger groups of days. Fig. 2 shows the average daily variation curves for the neutron monitor at Climax obtained by methods A and C for a 20-day interval and a 6-month interval. It will be seen that whereas for the 20-day interval the peak-to-peak amplitudes are 1.5% and 1.3% for methods A and C respectively, the amplitudes are almost equal for the 6-monthly period. It should be noted that the amplitudes obtained by method A need not necessarily be larger. Distortions due to gradients will enhance or reduce the amplitudes depending upon whether the phase of the extra contribution is similar or opposite to the phase of the genuine variation.

(2) *Study of the frequency distributions of the amplitudes and time of maxima of the diurnal and the semi-diurnal components of the daily variation.*

A useful way of studying the daily variation is by resolving the 12 bi-hourly percent deviations into Fourier (harmonic) components for every day and studying the frequency distributions of the amplitudes and time of maxima. However, such frequency distributions will suffer distortions if the general level of cosmic ray intensity is increasing or decreasing with constant gradients. The effects of linear gradienst can be estimated by subjecting to harmonic analysis idealised bi-hourly deviations giving straight line plots. Table I below gives such estimates for the amplitudes and time of maxima of the 1st and 2nd harmonics for positive and negative linear gradients of 1.0% over 24 hours.

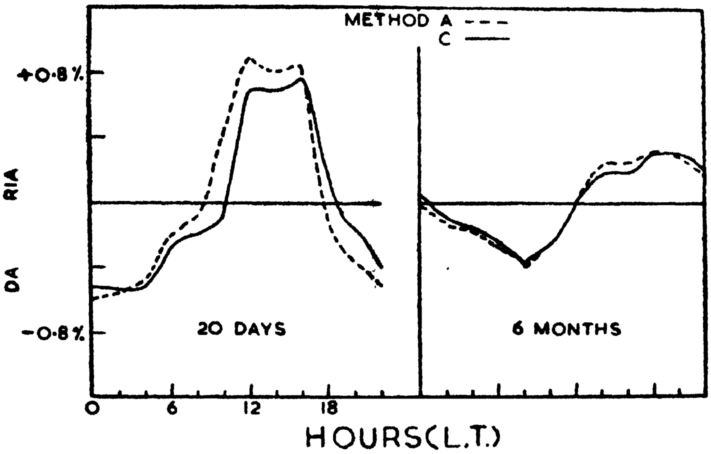

Fig. 2. Average daily variation for neutron intensity at Climax for a 20-day and a 6-month period.

TABLE I

	Amplitude r_1	Time of max. ϕ_1	Amplitude r_2	Time of max. ϕ_2
Linear increase of 1.0%/24 hours.	0.32%	$\pi + 75°$	0.17%	$\pi + 60°$
Linear decrease of 1.0%/24 hours.	0.32%	75°	0.17%	60°

In practice, these vectors will be superimposed upon the genuine diurnal and semi-diurnal vectors.

To see how these distortions occur in actual data, the bi-hourly values of neutron intensity at Climax were treated by methods A and C and harmonically analysed for individual days for a 12 month period. Fig. 3 shows the frequency distributions for the amplitudes (r_1 and r_2) and the time of maxima (ϕ_1 and ϕ_2) of the first and second harmonics respectively obtained by methods A and C. It will be noted that the amplitudes of the first harmonic extend to larger values in method A. Also the frequency distribution of the time of maximum ϕ_1 of the first harmonic has a larger spread in method A.

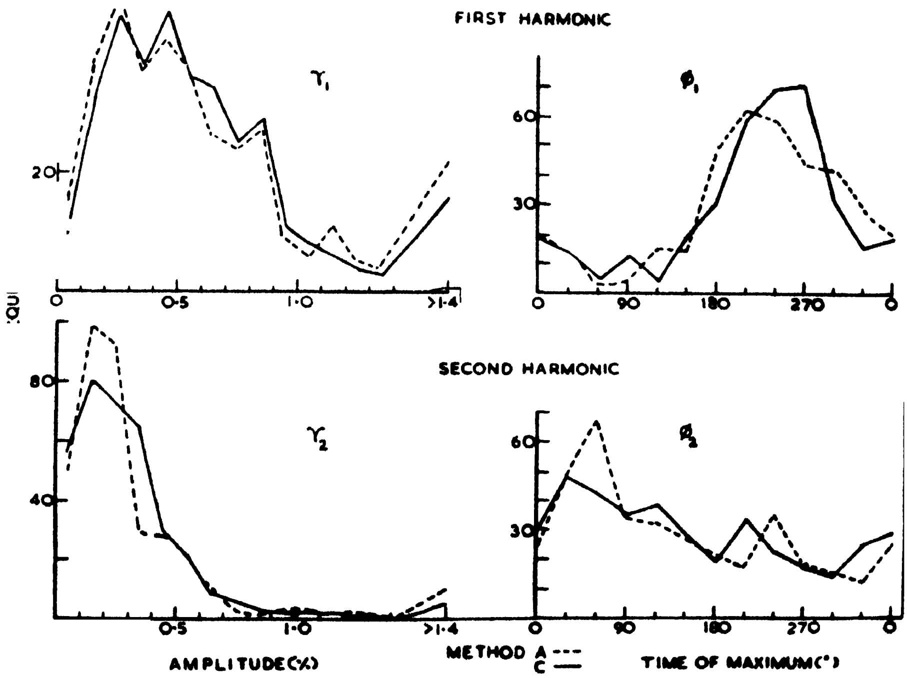

Fig. 3. Frequency distributions for the amplitudes (r_1 and r_2) and times of maxima (ϕ_1 and ϕ_2) for the first and second harmonics for Climax neutrons.

(3) *Relationship between daily variation and daily mean intensity.*

For studying a relationship of this type, it is obvious that method A is not suitable; because the daily variation is already distorted by gradients in daily mean intensity to the extent indicated in Table I.

(4) *Solar and Terrestrial relationships of daily variation*

It is well known that the daily mean intensity of comic rays is related to geomagnetic disturbances as well as some solar phenomena. If, therefore, the daily variation of cosmic rays is studied by method A, all such relationships will affect the characteristics of the daily variation also. Therefore, for this type of analysis, method A is not suitable.

(5) *Study of individual bi-hourly deviations*

As can be seen from Fig. 1, the individual bi-hourly deviations obtained by method A can be greatly distorted by the general trend in the daily mean intensity. Hence, method A is not suitable for this type of study.

It may be concluded, therefore, that except for periods when the fluctuations in the daily mean intensity are small compared to the expected amplitudes of daily variations or except when daily variations averaged over long periods are under consideration, the use of method A is undesirable for a study of the daily variation, as it is distorted by what may be termed as "Slope effects". Method B is better than method A but has its limitations as already referred to above. Method C is more rigorous and has a smaller Poisson standard error and hence is preferable to methods A and B for most purposes.

IV. A CRITICAL APPRAISAL OF METHOD C

It was shown in the previous section that amongst the three methods for obtaining the bi-hourly percent deviations from mean, method C is the best. However, it is necessary to examine whether method C is completely free from effects due to gradients.

The bi-hourly cosmic ray intensity $I'(t)$ observed at $U.T.(t)$ may be expressed as

$$I'(t) = I(t) + f(T, t)$$
$$= I(t) + \sum_n r_n \sin\{n(t+\psi) + \phi_n\} \qquad \dots \quad (1)$$

where $I(t)$ is the isotropic level of world-wide cosmic ray intensity and $f(T, t)$ is the daily variation, which can be resolved into Fourier components. Since all harmonics of periodicities of 24 hours or fractions thereof, reduce to zero when averages over 24 hours are taken, averages of $I'(t)$ over 12 successive bi-hourly values will be equal to similar averages of $I(t)$. In method C, it is assumed that such averages of $I'(t)$ values for 12 sucessive bi-hourly intervals are good estimates of the instantaneous values of $I(t)$ for the middle of the interval. Such an assumption is valid only when $I(t)$ changes occur with constant gradients. If the gradients (i.e. slopes) change, distortions will be produced which will be roughly proportional to the second derivative d^2I/dt^2 of the (I vs. t) plot. It is obvious, therefore, that method C will give incorrect results during periods when the gradients dI/dt undergo large changes.

The distortions produced due to changes in gradients can be broadly classified into 2 types:

(i) Long-term changes of world-wide cosmic ray intensity with time constant exceeding 24 hours. These will produce distortions which will be termed as "Curvature effects".

(ii) Short-term (hours-to-hour) fluctuations of a world-wide nature in the cosmic ray intensity. These will be termed as "Short-term effects".

The contribution of "Curvature effects" to the daily variation can be estimated if the pattern of the intensity change is known. Consider, for example, the patterns A and B shown in Fig. 4, which represent linear gradient schanging signs abruptly. In Fig. 4, pattern A corresponds to a constant gradient of

+0.1%/hr. for 18 successive bi-hourly values, followed by a sudden change to a constant gradient of −0.1%/hr. for the next 18 bi-hourly values. This pattern corresponds to a change of about 2.4% per day which is not uncommon for cosmic ray neutron intensity at high latitudes. Pattern B corresponds to a form exactly opposite to pattern A.

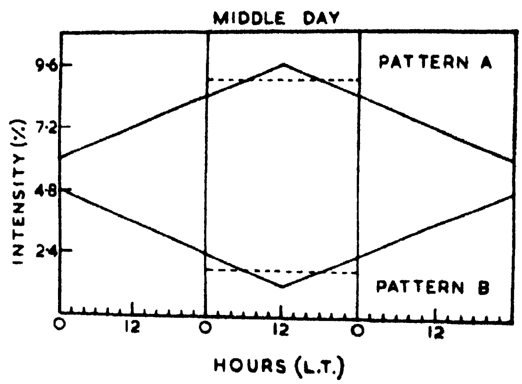

Fig. 4. Sample patterns of sudden changes in the linear gradients of cosmic ray intensity.

If the point of inflection is assumed to coincide with 12 noon (L.T) for the middle day and the data are treated by method C and the bi-hourly percent deviations harmonically analysed, the amplitudes and time of maxima of the first and second harmonics for the middle day are as given in Table II.

TABLE II

	1st harmonic		2nd harmonic	
	Amp.	Time of max.	Amp.	Time of max.
Pattern A	0.24%	180°	0.08%	0°
Pattern B	0.24%	0°	0.08%	0°

It will be seen that amplitudes of the order of 1/4% can arise due to "Curvature effects" on individual days, if the day includes the inflection point. For other days, as also for averages over groups of days, the contribution due to "Curvature effects" will be negligible.

As regards the contribution of "Short-term effects" to daily variation, it is difficult to investigate patterns as there are innumerable ways in which individual bi-hourly values can be affected by world-wide short-term fluctuations of isotropic cosmic ray intensity. From the data from a single station it is impossible to estimate the contribution of such changes to individual bi-hourly values.

V. AN EFFECTIVE METHOD OF ESTIMATING THE WORLD-WIDE SHORT-TERM CHANGES OF COSMIC RAY INTENSITY

As seen in previous section, data from a single station are inadequate to separate out the genuine daily variation of cosmic ray intensity from its experimentally obtained form distorted by possible "Short-term and Curvature effects". For long-term averages, such effects are expected to even out, but for averages over only a few days, there is a possibility of distortions. Unfortunately, it is not possible to estimate their magnitude from the data of a single station.

A little consideration shows, however, that there is a possibility of such an estimate if data from more than one station are utilised. This is already pointed out by Sekido *et al.* (1952). Referring back to Eq. (1), let us assume that cosmic ray data are available for a number of stations which are at the same geomagnetic latitude and are at equally spaced longitudes all round the globe. Then, the cosmic ray intensity $I'_K(t)$ at the k-th station at time (t) would be given by

$$I'_K(t) = I(t) + \sum_n r_n \sin\{n(t+\psi_k)+\phi_n\} \qquad \ldots \quad (2)$$

where r_n and ϕ_n represent the amplitude and phase of the nth harmonic for a station of longitude zero ($\psi_0 = 0$) and ψ_k is the longitude of the kth station. If values of ψ_k for successive stations differ by a constant quantity $360/m$, where m is the number of stations, then

$$\psi_k = (k-1)\frac{360}{m} \qquad \ldots \quad (3)$$

and

$$\sum_{k=1}^{m} r_n \sin\left[n\left\{t+\frac{360(k-1)}{m}\right\}+\phi_n\right] = 0 \qquad \ldots \quad (4)$$

for $n \neq \beta m$, where β is a positive integer,

provided that the amplitudes r_n and phases ϕ_n remain constant for more than 24 hours. Thus, if we concentrate our attention only on the first harmonic($n = 1$), even two stations ($m = 2$) separated by $360/m = 180°$ will ensure that Eq. (4) is satisfied. To eliminate the second harmonic also ($n = 2$), we will need 3 stations, 120° apart in longitude. If data from 3 such stations are available, then the average of the percent cosmic ray values at the 3 places for *the same universal time* (t) will be devoid of the first or second harmonic of genuine daily variation.

It is obvious, therefore, that if the world-wide bi-hourly percent mean intensity obtained by adding the percent values at the same U.T. of 3 stations at roughly the same geomagnetic latitude and spaced 120° apart in geographic longitude is subjected to an analysis of daily variation by method C, one would get an idea of the characteristics of the *apparent* daily variation introduced due to short-term and curvature effects of the world-wide isotropic intensity changes. With this view, data obtained during I.G.Y. were examined to select out suitable groups of stations. A study of the geographical distribution of neutron monitor stations shows that there is a preponderance of stations in the European and American longitudes but a marked scarcity in the Far East. The following factors have also to be kept in mind :

(a) The stations should be at roughly the same geomagnetic latitude to ensure similar cut-off energies.

(b) They should have similar energy responses related to the altitude.

(c) They should have been corrected for barometric effect by the same pressure coefficients (say, $0.72 \pm 0.02\%/mb.$ Hg.).

(d) Data for each of them should be fairly continuous for about 12 months to give a large number of common days.

(e) The counting rate at each station should be fairly high (bi-hourly standard error about 0.5%).

(f) They should be $120° \pm 10°$ apart in geographic longitude.

It was found that the following stations could be utilised for analysis:

(1) Lincoln or Climax in Americas.

(2) Gottingen or Weissenau and some others in Europe.

(3) Yakutsk in the Far East.

From the point of view of spacing in geographical longitude, Climax, Gottingen and Yakutsk is a very convenient group. Since Climax is a high altitude station, Lincoln, Gottingen and Yakutsk is perhaps a more appropriate choice. Table III gives the details about the geographical locations and energy responses etc. for the 4 stations.

TABLE III

Station	Geomag. latitude	Geographical longitude	Altitude (meters)	Cut-off energy (BeV)	Mean Fonger energy response (BeV)
Climax	48°	106°W	3400	3.0	9.7
Lincoln	51°	97°W	350	2.6	12.1
Gottingen	52°	10°E	273	2.4	12.1
Yakutsk	51°	129°E	105	2.2	12.1

The bi-hourly values for Climax, Lincoln, Gottingen and Yakutsk were obtained from the Japanese publication "Cosmic Ray Intensity during the

I.G.Y.—No. 1-2″. Values for the same bi-hourly (G.M.T.) intervals were added to yield bi-hourly values of W and W′ series defined as follows :—

$$W = \tfrac{1}{3}\,(\text{Climax}+\text{Gottingen}+\text{Yakutsk})$$

$$W' = \tfrac{1}{3}\,(\text{Lincoln}+\text{Gottingen}+\text{Yakutsk})$$

If the pattern of daily variation remains constant for more than 24 hours, the bi-hourly values of W or W' would be devoid of the 1st. 2nd. 4th and 5th harmonics. The 3rd and 6th harmonics will be retained.

The bi-hourly values of W and W' were treated by method C and the percent bi-hourly deviations obtained for the 12 successive bi-hourly intervals centered at 01, 03...23hr. G.M.T. were considered as a U.T. apparent daily variation* which would give a measure of the distortion involved on any particular date. Except for the fact that the 3rd and 6th harmonics are still retained in W or W' and that some discrepancies would creep in, if the genuine daily variation is of a transient type (this is discussed further in Sec. VII), the characteristics of the daily variation exhibited by W or W' would give an estimate of the "Curvature and Short-term effects" that vitiate the genuine daily variation. In the next section, results obtained for the 12 month period July 1957—June 1958 are described.

VI. CHARACTERISTICS OF THE APPARENT DAILY VARIATION DUE TO "CURVATURE AND SHORT-TERM EFFECTS"

(1) *Variance of daily variation* :

A useful criterion for studying the magnitude of daily variation is the variance which we define as

$$V = \sum_{x} \; (\delta I_x)^2$$

where (δI_x) is the percent deviation from the day's mean for the bi-hour x. V is a gross measure of the daily variation on any particular day without any reference to the phase of the daily variation, and apart from the contribution due to random statistical fluctuations, is a good measure of the average disturbance.

Variances have been calculated for the world-wide isotropic neutron intensities W and W' as also for the neutron intensities at Climax, Gottingen, Lincoln and Yakutsk. The frequency distributions of V for the period July 1957 to June 1958 are shown in Fig. 5. It will be seen that the variance of the apparent daily variation of W or W' is not negligible and there is an indication that a portion of the daily varia-

* Recently, Parsons (year?) has attempted to estimate the U.T. contribution to the monthly average daily variation curves for the experimental data of several high latitude neutron monitor stations.

tion observed on individual days is attributable to curvature and short-term effects.

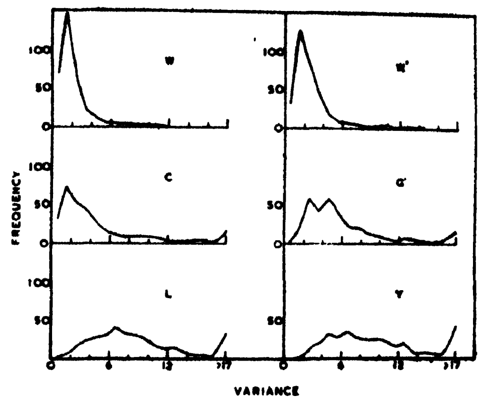

Fig. 5. Frequency distributions of variances for W, W', Climax (C), Lincoln (L), Gottingen (G) and Yakutsk (Y).

(2) *Amplitudes and times of maxima of daily variation* :

A convenient way of studying the daily variation vector is to resolve the 12 bi-hourly values into the first and second harmonics by the usual methods of Fourier analysis. This can be done either for individual days or for averages over a number of days. It would be interesting to see how much of the daily variation on individual days is contributed by short-term and curvature effects. To study this, the percentage bi-hourly deviations for the intensity W and W', treated by method C, were harmonically analysed for every day for which full data were available during July 1957 to June 1958. Fig. 6 shows the frequency distributions for r_1, r_2, ϕ_1 and ϕ_2 i.e., the amplitudes and times of maxima of the first and second harmonics. For comparison, similar distributions for neutron intensity at Climax, Lincoln, Gottingen and Yakutsk for the same period, are shown. It will be noticed that the amplitudes r_1 and r_2 for W and W' are not negligible compared to those for Climax, etc. This confirms our earlier conclusion drawn from the variance distribution that the daily variation on individual days is partly due to short-term and curvature effects as depicted by W and W'. It must be emphasised here that these apparent amplitudes cannot be attributed to random statistical fluctuations. From the known bi-hourly counting rates at the various stations, the Poisson standard errors of the amplitudes on individual days can be calculated. The 2σ levels are indicated in Fig. 6 by vertical dotted lines in the r_1, r_2 frequency distributions. It will also be observed that the distribution of the times of maxima for W and W' shows, as expected, no preference for any particular hours, while for Climax, etc., directions near local noon are favoured most for the first harmonic.

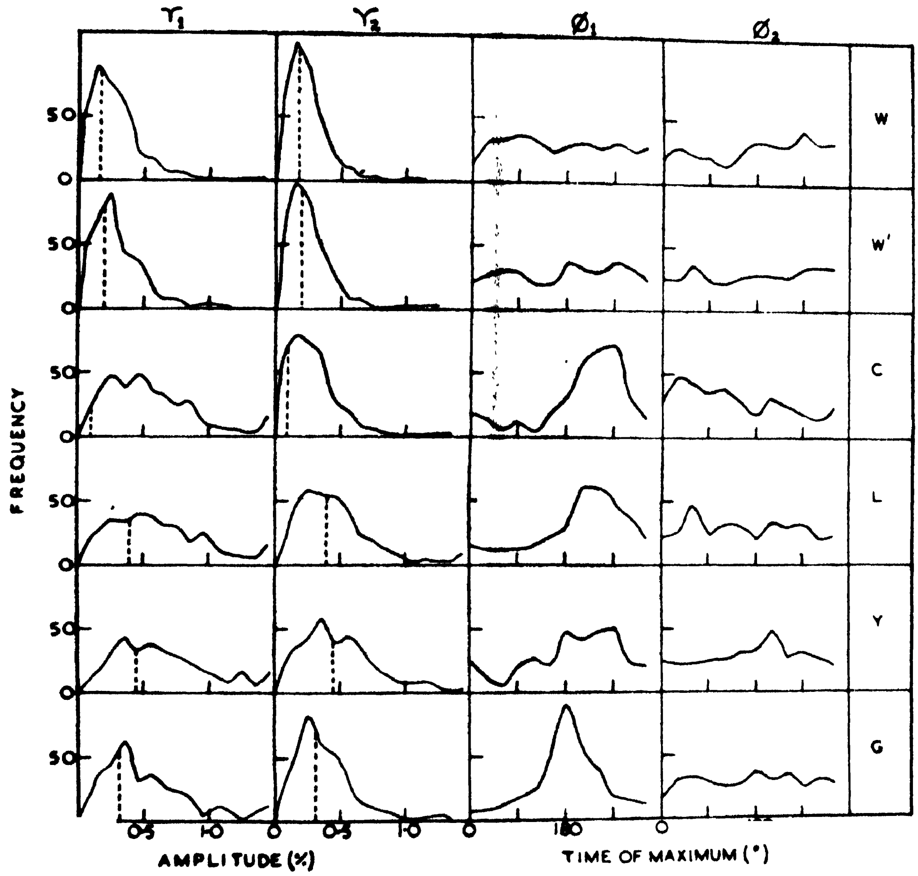

Fig. 6. Frequency distributions for the amplitudes (r_1, r_2) and times of maxima (ϕ_1, ϕ_2) of the first and second harmonics for W, W', Climax, Lincoln, Gottingen and Yakutsk. Vertical dotted lines in r_1, r_2 distributions are 2σ limits.

(3) *Monthly mean daily variation* :

It will be interesting to estimate the contribution of the apparent daily variation when averages over groups of days are considered. Table IV gives the amplitudes and the times of maxima of the 1st and 2nd harmonics of the monthly average daily variations for W, W' and Climax for July 1957 to June 1958. It will be seen that the monthly averages for W and W' are not negligible. The amplitudes for W and W' are about ⅓rd of those for Climax for individual months but less than 1/5 th for the yearly averages. It is clear, therefore, that the apparent daily variation depicted by W and W' progressively reduces in amplitude

TABLE IV

Month	W				W′				Climax			
	r_1(%)	ϕ_1	r_2(%)	ϕ_2	r_1(%)	ϕ_1	r_2(%)	ϕ_2	r_1(%)	ϕ_1	r_2(%)	ϕ_2
July, 1957	0.12	$\pi+65^\circ$	0.06	$\pi+34^\circ$	0.13	$\pi+94^\circ$	0.08	$\pi-7^\circ$	0.36	$\pi+57^\circ$	0.13	30°
August	0.14	$\pi-21$	0.09	$\pi+32^\circ$	0.16	$\pi+47^\circ$	0.05	$\pi-53^\circ$	0.49	$\pi-54^\circ$	0.08	68°
September	0.04	135°	0.08	$\pi+50$	0.03	$\pi+45^\circ$	0.06	$\pi-59^\circ$	0.57	$\pi+32^\circ$	0.13	103
October	0.02	90	0.05	$\pi+53^\circ$	0.02	27°	0.06	$\pi+45$	0.37	$\pi+54^\circ$	0.03	135°
November	0.07	27	0.08	$\pi+90^\circ$	0.05	-11	0.08	$\pi-67$	0.42	$\pi+43^\circ$	0.12	96°
December	0.12	95	0.02	$\pi-27^\circ$	0.09	117°	0.02	$\pi-90^\circ$	0.09	$\pi+20^\circ$	0.07	21°
January, 1958	0.03	$\pi+71$	0.03	$\pi-18^\circ$	0.09	144	0.04	56°	0.34	$\pi-75^\circ$	0.06	15°
February	0.15	53	0.05	$\pi+37^\circ$	0.06	-9°	0.07	-34°	0.48	-34°	0.13	156°
March	0.06	$\pi+9^\circ$	0.04	$\pi+27^\circ$	0.09	$\pi+32^\circ$	0.02	$\pi-63^\circ$	0.23	$\pi+76^\circ$	0.07	-7°
April	0.04	-27°	0.07	-63°	0.05	-53	0.05	-79°	0.34	$\pi+72^\circ$	0.05	130°
May	0.03	109°	0.05	-53°	0.06	$\pi-9^\circ$	0.04	-56°	0.29	$\pi+91^\circ$	0.06	139°
June	0.12	104°	0.05	-90°	0.10	151°	0.03	-45°	0.49	-56°	0.09	86°
Yearly average	0.03	108°	0.04	$\pi+63^\circ$	0.03	$\pi-18^\circ$	0.03	$\pi-90^\circ$	0.32	$\pi+69^\circ$	0.06	83°

when averages over large periods (about an year) are obtained. For smaller periods, considerable distortions can occur.

(4) *Contribution of the apparent daily variation to averages over groups of days selected on physical criteria* :

For studying solar and geomagnetic relationships of the daily variation, the usual procedure is to select groups of days according to certain criteria and evaluate the average daily variations. For example, one could compare average daily variations on magnetically disturbed and quiet days. One could attempt to find correlated changes between daily variation and daily mean intensity and so on. Several workers have reported results of these types in the past.

It must be noted, however, that in some of these criteria the days selected are such that they are associated with large gradients and curvatures of cosmic ray intensity. For these, the apparent daily variation due to curvature and short-term effects is expected to be large. A preliminary analysis conducted by us for groups of days selected on the usual geomagnetic criteria has indicated that many of the characteristics reported for daily variation for days conforming to such criteria are shown to some extent by the apparent daily variation also. This does not exclude the possibility that such characteristics will be depicted by genuine daily variation. It needs to be confirmed, however, that such characteristics are still shown when the observed daily variation is corrected for effects due to the apparent daily variation.

It must be pointed out here that the estimates of the apparent daily variation due to short-term and curvature effects as given above are only for middle latitude, neutron monitor intensities. The effects are roughly proportional to the range of fluctuations of cosmic ray intensity. Since the daily mean intensities of neutron component and meson component at equator show fluctuations about $\frac{1}{2}$ and $\frac{1}{3}$ to $\frac{1}{4}$ respectively of the mean intensity fluctuations of neutron intensity at middle latitudes, it would seem that the distortions due to apparent daily variation would be lesser in the above proportions for equatorial neutrons and mesons. This will certainly be true for curvature effects which are of periodicities greater than 24 hours. For short-term fluctuations, it requires to be checked whether hour-to-hour changes of world-wide isotropic intensities have also the same latitude dependence as fluctuations of daily mean intensity.

VII. METHOD OF STUDYING THE GENUINE DAILY VARIATION OF COSMIC RAY INTENSITY

It is clear from the above discussion that the daily variation of cosmic ray intensity can be in error when studied for short periods from the data of only one station. The results will be distorted due to the presence of an apparent daily variation due to world-wide fluctuations of isotropic intensity. The magnitude of the latter can be estimated by combining data from three or more stations at roughly the same geomagnetic latitude and equally spaced in geographical longitudes. On the other hand, to eliminate the contribution of the apparent daily variation and to study the genuine daily variation of cosmic ray intensity, it would be necessary to subtract the world-wide intensity fluctuations from the original data of any one station. To give a specific example, we have, in the present communication, combined the data from the stations Climax Gottingen and Yakutsk for similar bi-hourly intervals (U.T.) to obtain the series W. One could now subtract the bi-hourly values of W from the bi-hourly values of Climax, Gottingen or Yakutsk for the same U.T. and obtain series of bi-hourly values which, when considered according to the local time of the particular station would give the basic 12 bi-hourly values for study of the daily variation. To improve the statistics, one could superimpose the local time bi-hourly values of the three stations. On the other hand, since the daily variation may be of a transient nature, one may prefer to study the data obtained for the three stations individually and observe the 8 hourly changes in the nature of the daily variation. Such an analysis may prove very fruitful for studying the influence of S.C. storms as well as solar flares which are comparatively of short duration.

It is necessary, however, to discuss at this stage the merits and demerits of this method for all aspects of the study of daily variation. The necessity of adopting the present method arises from the existence of short-term and long-term world-wide changes in the mean level of isotropic cosmic ray intensity. Also, its success depends upon its ability to eliminate these changes without eliminating a genuine daily variation. This is achieved if the genuine daily variation is of a constant pattern. In practice, however, one is likely to encounter complex patterns of daily variation. It is necessary to study in detail the various types of effects that one may observe in daily data. Since the basic data are averaged over a bi-hourly interval, we will consider bi-hourly percent deviations as our basic unit. Samples of various cases are illustrated in Fig. 7, where C, G and Y represent bi-hourly values at Climax, Gottingen and Yakutsk respectively, for the same U.T. indicated on abscissa, and W represents the average given by

$$W = \tfrac{1}{3}(C+G+Y)$$

(i) Climax, Gottingen and Yakutsk all show a positive (or negative) bi-hourly deviation of the same magnitude at a particular bi-hourly interval. Then W will also show a similar deviation at the same hour. This is illustrated in Fig. 7(i) and is a true world-wide effect with magnitudes remaining the *same* for C, G, Y, as also for W.

(ii) Climax shows a bi-hourly deviation at a particular hour U.T. and Gottingen and Yakutsk show the same deviation but 8 and 16 hours

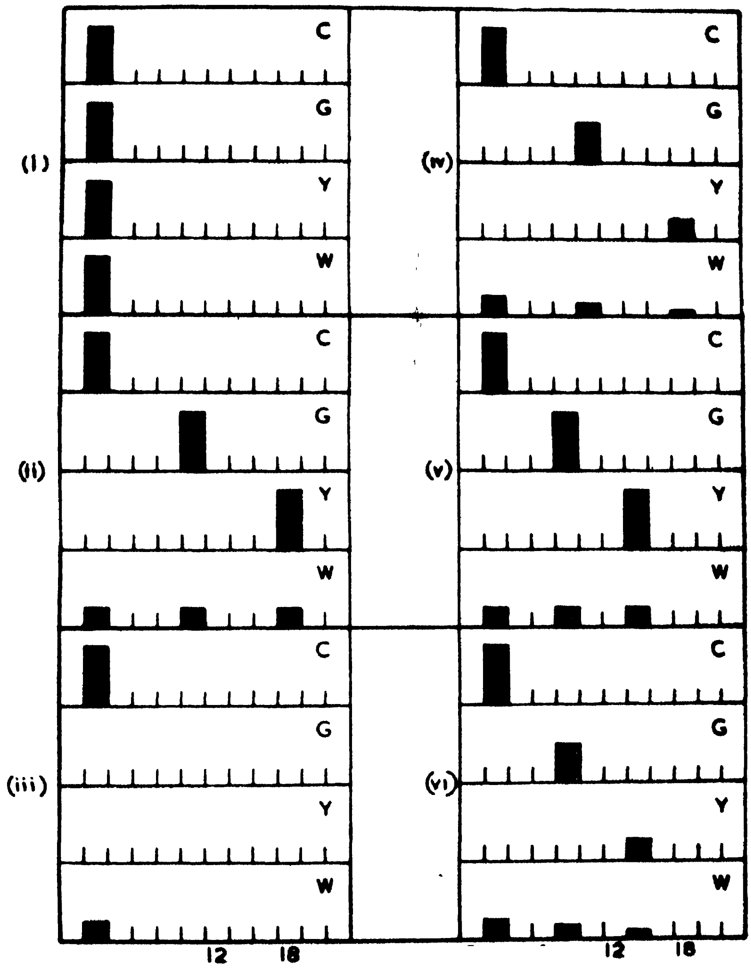

Fig. 7. Sample patterns of bi-hourly deviations for Climax (C), Gottingen (G), Yakutsk (Y) and their average (W).

later respectively. This is a genuine L.T. daily variation effect. It is illustrated in Fig. 7 (ii) and its effect on W will be to produce three humps 8 hours apart and 1/3rd in size. If harmonically analysed, the W curve for such a day will show an absence of 1st, 2nd, 4th and 5th harmonic. The 3rd and 6th harmonics will be present.

(iii) Climax shows a bi-hourly deviation at a particular hour U.T. but Gottingen and Yakutsk do not show any effect at this hour or 8 and 16 hours later. This is an impact zone type effect where Climax was in a location suitable for observing the effect but Gottingen and

Yakutsk were not. This is illustrated in Fig. 7 (iii) and produces a deviation in W of magnitude about 1/3rd of that at Climax. This could as well occur at Gottingen or Yakutsk and in each case, W curve will be biased towards that station.

It should also be noted that for individual bi-hourly values, such an impact zone effect cannot be distinguished from high positive or negative deviations occurring at different stations at certain hours due to instrumental troubles unless data from stations in about the same geographical region and altitude are available for comparison.

(iv) Climax shows a bi-hourly deviation at a particular hour U.T. and Gottingen and Yakutsk show reduced or negligible amplitudes 8 and 16 hours later. This is a genuine daily variation, the amplitude of which is changing rapidly, during the course of a few hours [Fig. 7 (iv)]. In this case, the various harmonics will not cancel out in the average curve W. In fact. W will show roughly the same type of variation as in (iii) above.

(v) Climax shows a bi-hourly deviation at a particular hour U.T. and Gottingen and Yakutsk show the same amplitudes but not 8 and 16 hours later, but somewhat earlier [Fig. 7(v)]. This is a case where a genuine daily variation is constant in amplitude but has a *changing phase*. Here again, the daily variation will not cancel out in W but will leave a residual variation of about 1/3rd amplitude. In extreme cases where phase shifts are very large, the effect in W could be comparable in magnitude to that at Climax or Gottingen or Yakutsk.

(vi) One could imagine cases where both the amplitudes and phases change rapidly in the course of a few hours as in Fig. 7(vi). Here again the maximum amplitude in W would be lesser than the maximum disturbance among the three stations.

If now an attempt is made to study the genuine daily variation by subtracting W curve from the C, G and Y curves and considering $(C-W)$, $(G-W)$ and $(Y-W)$ as representative of the *genuine* daily variations for Climax, Gottingen and Yakutsk respectively, the following will happen:

(i) The genuine daily variation so obtained will be completely free from any distortion effects due to *world-wide* changes of cosmic ray intensity. This will be true for individual bi-hourly values and hence for all the harmonics of a daily variation.

(ii) If the daily variation is constant in amplitude and phase for more than 24 hours, this method will give correct results for the 1st, 2nd, 4th and 5th harmonics. The 3rd and 6th harmonics will, however, be missing. For individual bi-hourly deviations, this method will show such deviations reduced to about 2/3rd of their original values.

(iii) If the genuine daily variation is of a rapidly changing pattern, the effect of the present method will be again to reduce the amplitudes to about 2/3rd of their original values. This will roughly be true for bi-hourly deviations as also for the various harmonics. In the case of the latter, distortions in phases would also be expected.

(iv) All abnormalities like impact zone effects or bi-hourly deviations due to faulty data will be reduced to about 2/3rd of their original values.

Therefore, while taking a decision as to whether one should study daily variation of cosmic ray intensity by the present method or by the usual method C adopted for individual stations, one has to choose between two alternatives viz., to eliminate world-wide short-time fluctuations of cosmic ray intensity but in this process to reduce the amplitudes of the *rapidly changing portion* of daily variation to about 2/3rd of its original amplitude or, to retain fully all genuine daily variation but allow distortions due to world-wide short term fluctuations of isotropic intensity. Such a decision would largely depend upon the relative magnitudes of the genuine daily variation and the apparent daily variation produced by short-term world-wide fluctuations. It would be worthwhile getting an estimate as to how often world-wide short term fluctuations occur in a given data. For this purpose the data for W as described in the present paper were considered as follows:

Since the Poisson bi-hourly standard errors of Climax, Gottingen, Yakutsk and W are 0.12%, 0.41%, 0.56% and 0.24% respectively, amplitudes of about 0.3% and 0.5% or more, are significant on a 2σ level (95% surety) for Climax and W respectively, but not for Gottingen and Yakutsk. However, since the standard error of *Gottingen plus Yakutsk* is about 0.69%, a value of 1.4% or more for this *sum* would be significant on a 2σ level. Hence, days were selected on which at least one bi-hourly deviation for W exceeded 0.5% numerically. Such days were termed as disturbed days. Now, W is related to Climax, Gottingen and Yakutsk as

$$W = \tfrac{1}{3}(C+G+Y).$$

Therefore, it was further examined whether a particular large bi-hourly deviation of W was largely due to C (Climax) or due to Gottingen and/or Yakutsk or due to all the three. The following categories were obtained :

Category (a) : (**W due to world-wide isotropic change.**)	**For positive W values,** (i) $W \geqslant +0.6\%$ (ii) $C \geqslant +0.3\%$ (iii) $(3W-C) > +1.4\%$	**For negative W values,** (i) $W \leqslant -0.6\%$ (ii) $C \leqslant -0.3\%$ (iii) $(3W-C) < -1.4\%$
Category (b) : (**W attributable to Climax only**)	**For positive W values.** (i) $W \geqslant +0.6\%$ (ii) $C \geqslant +0.3\%$ (iii) $(3W-C) < +1.4\%$	**For positive W values,** (i) $W \leqslant -0.6\%$ (ii) $C \leqslant -0.3\%$ (iii) $(3W-C) > -1.4\%$
Category (c) : (**W due to Gottingen and/or Yakutsk only**)	**For positive W values,** (i) $W \geqslant +0.6\%$ (ii) $C < +0.3\%$	**For negative W values,** (i) $W \leqslant -0.6\%$ (ii) $C > -0.3\%$

On actually separating out the experimental data by the above criteria, the following statistics were obtained:

Total No. of days for which data were available	318
Total No. of days on which not a single bi-hourly for W exceeded 0.5% numerically (Quiet days)	61
No. of disturbed days	257
No. of days of Category (a) (W world-wide)	121
No. of days of Category (b) (W Climax-dominated) ...	94
No of days of Category (c) (W dominated by Gottingen or Yakutsk)	178

It is obvious, however, that many days are common to the three categories (a), (b) and (c). A further breakdown was therefore attempted and yielded the following results :

Total No. of disturbed days.		257
Category A :	Days on which one or more bi-hourly deviations of W were due to all the three stations (exclusive world-wide effect)	39
Category B :	Days on which one or more bi-hourly deviations of W could be attributed to Climax *exclusively*.... ...	28
Category C :	Days on which one or more bi-hourly deviation of W could be attributed *exclusively* to Gottingen and/or Yakutsk.	80
Category D :	Days on which some bi-hourly deviations were due to Climax and some due to world-wide effect. (a)+(b) category.	12
Category E :	Days on which some bi-hourly deviations were due to Climax and some due to Gottingen and/or Yakutsk. (b)+(c) category.	28
Category F :	Days on which some bi-hourly deviations were due to world-wide effect and some due to Gottingen and/or Yakutsk. (a)+(c) category.	44
Category G :	Days on which some bi-hourly deviotions were due to Climax, some due to world-wide effect and some due to Gottingen and/or Yakutsk. (a))+(b)+(c) category.	26
	Total (A+......G)	257

It seems, therefore, that almost all types of variations are present in the data in various degrees. Thus, categories B, C and E are solely due to fluctuations at Climax, or Gottingen or Yakutsk. Due to lack of statistical accuracy, it is impossible to judge which of these are due to genuine daily variation of constant pattern and which are due to genuine daily variation of rapidly changing pattern. Also, all impact zone effects as well as abnormal fluctuations due to faulty data would be included here! Category A represents days *exclusively* of the world-wide type while categories D. F and G are of a world-wide as well as individual type, category G having the utmost disturbance.

The effect of each one of these categories on the results of daily variation studied by the present method is already discussed above. It would be interesting to see what is the contribution of these to the amplitudes of the first harmonic of daily variation of W. Since frequency distribution for a few days would not be very meaningful nor are the categories completely unambiguous, the various categories referred to above were grouped as follows :

Group 1...Category B, C, E ... Days 136

Group 2...Category A, D, F, G ... Days 121

Fig. 8 shows the frequency distribution of r_1, the first harmonic of the daily variation of W for the two groups. It will be seen that the amplitudes of Group 1 which contains effects on W of L.T. variations at all the three stations as also impact zone and faulty data effects, are confined to lower magnitudes than the amplitudes of Group 2 which represents world-wide fluctuations.

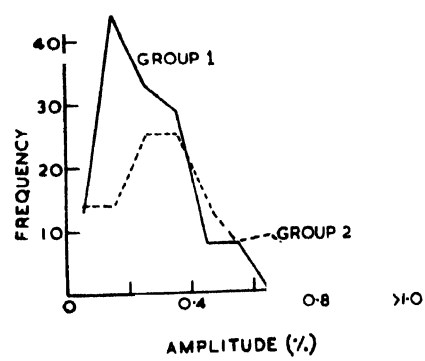

Fig. 8. Frequency distribution of the amplitude of first harmonic (r_1) of W for Groups 1 and 2.

It would seem, therefore, that on almost half the number of disturbed days (121 in 257), the large values of W are either fully or partly due to world-wide effects which can produce apparent amplitudes as large as 0.5% for the first harmonic of daily variation. It would hardly be necessary to emphasise the necessity of correcting for this effect by subtracting W from the individual stations. On the other hand, such a procedure would reduce the amplitudes of the changing type of daily variation for 218 days (Categories B, C, D ,E, F, G) to about 2/3rd of their original values. For many of these days, the amplitudes will be due to instrumental faults, because as shown in an earlier publication (Kane, 1960), many of the I.G.Y. neutron monitor stations have discrepancies of the order of 1—2% in their bi-hourly values. Also, there will be no reduction in amplitude or distortions of phase for the 1st, 2nd, 5th and 6th harmonics if the genuine daily variation has not changed its pattern radically during the course of a day. The reduction will be only for genuine daily variation patterns which change rapidly within a few hours. Due to statistical uncertainties, it is impossible to estimate the number of days on which only such patterns existed.

The choice is, therefore, between allowing apparent daily variations of amplitudes as high as 0.5% to distort the genuine daily variation or to eliminate the apparent variation and in this process, reduce the amplitudes of genuine daily variations of rapidly changing patterns to about 2/3rd their original value. The present author feels that the latter would be the lesser evil. The reduction effect given by $\left(1 - \frac{1}{m}\right)$ when m = Number of stations could be greatly minimised if data from more than three stations equally spaced in geographic longitude and confined to roughly the same geomagnetic latitude were available for analysis. Unfortunately, in the grid of I.G.Y. neutron monitor stations, it is difficult to pick out even groups of three equally spaced stations. The best one can do is to concentrate on groups like Climax (or Lincoln), Gottingen, Yakutsk and to study the daily variation after subtracting from each one of these the corresponding W curve. Work in this direction is in progress.

VIII. CONCLUSION

The results of the present analysis may be summarised as follows :

(1) Except for studying averages over very long periods (about an year), it is necessary to apply corrections for the slope, curvature and short term effects due to world-wide fluctuations of mean cosmic ray intensity.

(2) The slope effects can be effectively corrected for by assuming linear changes as done in method B or method C. The curvature effects are difficult to correct but are fortunately of a small magnitude ($\sim$0.2%). The short-term world-wide effects are the most important ones, on occasions, as large as 0.5% for neutrons at middle latitudes, and cannot be corrected for unless data from stations in the same geomagnetic latitude belt and equally spaced in geographic longitude are available.

(3) For studying only the first harmonic of daily variation, two stations 180° apart are adequate. If, however, higher harmonics are to be considered, the number of stations should be at least three. In view of the several complicated patterns of daily variation which are known to exist, the larger the number of stations, the better. Unfortunately, the present distribution of neutron monitor stations in the world is not quite adequate for this purpose. Attention is drawn of active workers

in this field to the gaps in the longitudinal distribution of cosmic ray recording instruments.

(4) An analysis of data from Climax, Gottingen and Yakutsk indicates that the curve W obtained as an average of these three, exhibits an apparent daily variation having some characteristics similar to those reported as belonging to the genuine daily variation of cosmic ray intensity. It seems necessary to correct for the apparent daily variation produced due to world-wide fluctuations of isotropic cosmic ray intensity.

(5) The magnitude of the distortions is directly proportional to the fluctuations of isotropic intensity. Fluctuations of daily mean intensity are roughly in the proportion 1 : 2 for equatorial and high latitude neutron intensities. Therefore, distortions due to slope and curvature effects would be about half at equatorial stations. For meson intensity the effects would be still less. It is not known, however, whether the short-term (hour-to-hour) fluctuations have the same latitude dependence as the daily mean intensities. This needs further scrutiny.

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